NPL OPTIMUM – Optical Tracking Instrument for Measurement Using Multilateration

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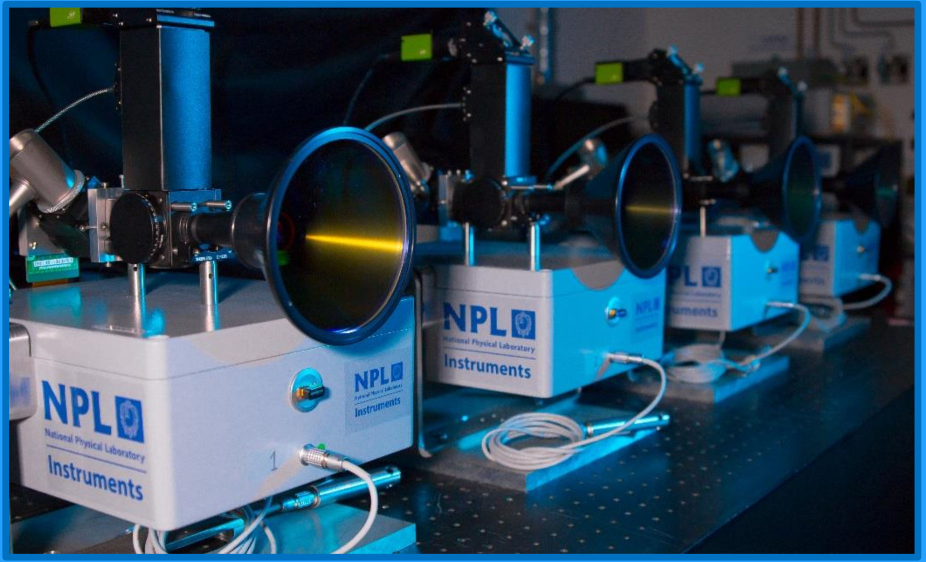
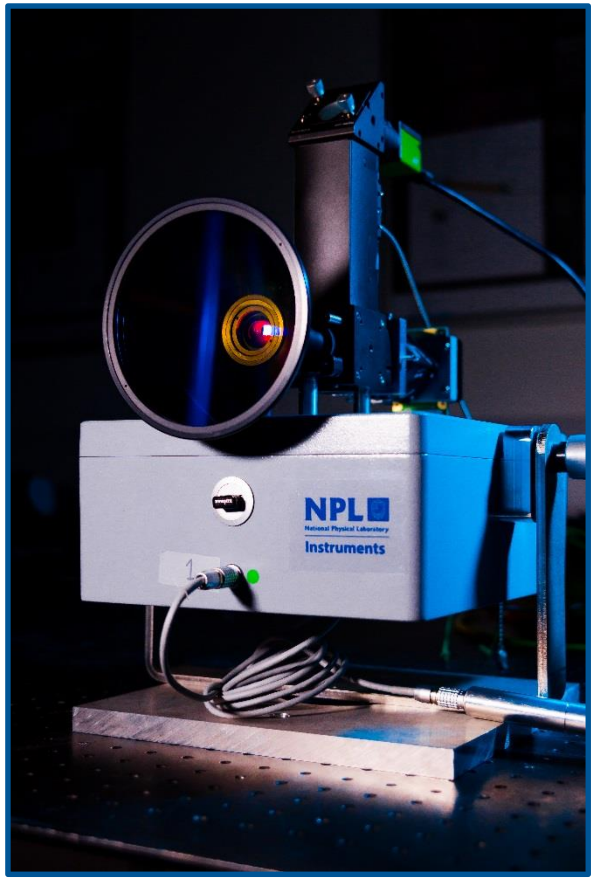


3DMC - Aachen

11th October 2017

Outline

- Introduction
- NPL's Proposed Coordinate Metrology System
  - Multilateration
  - Frequency Scanning Interferometry
- Results
- Conclusion



Introduction

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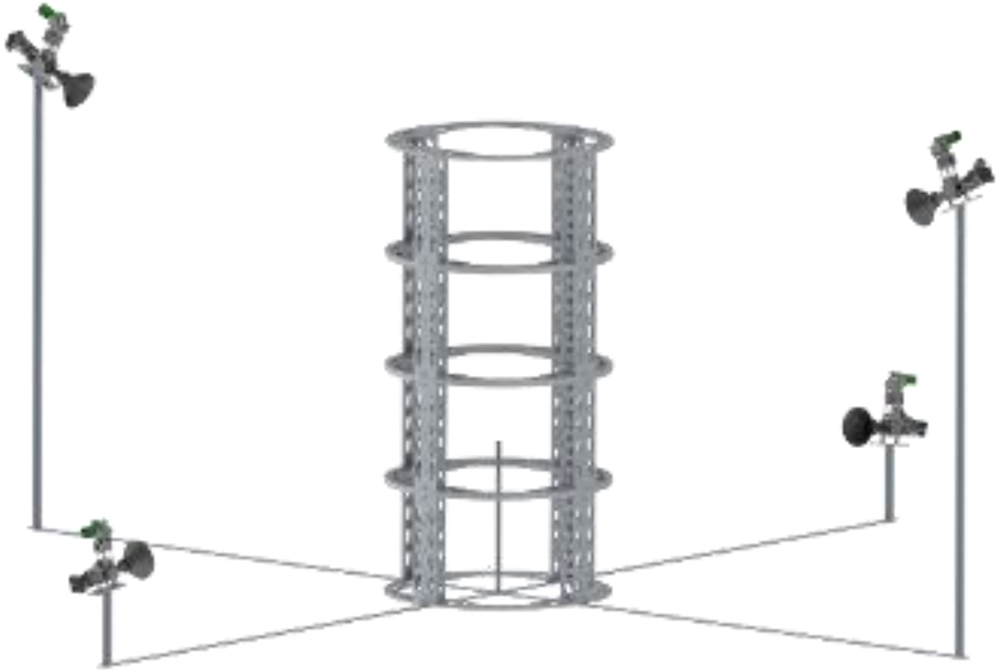
- How good is my instrument?
- What’s my measurement uncertainty?
- How can I be sure my calibration is still valid?

NPL OPTIMUM

- Objective is to make a CMS that is:
  1. As accurate as possible
  2. Measures multiple points simultaneously
  3. Self-calibrating - built-in compensation for systematic errors
  1. Has built-in traceability to SI metre
  2. Gives on-line uncertainty estimation

  Proposed Solution:
  - Multilateration
  - Frequency scanning interferometry



Aim for an operating volume of 10 m x 10 m x 5 m and uncertainty of < 50 µm

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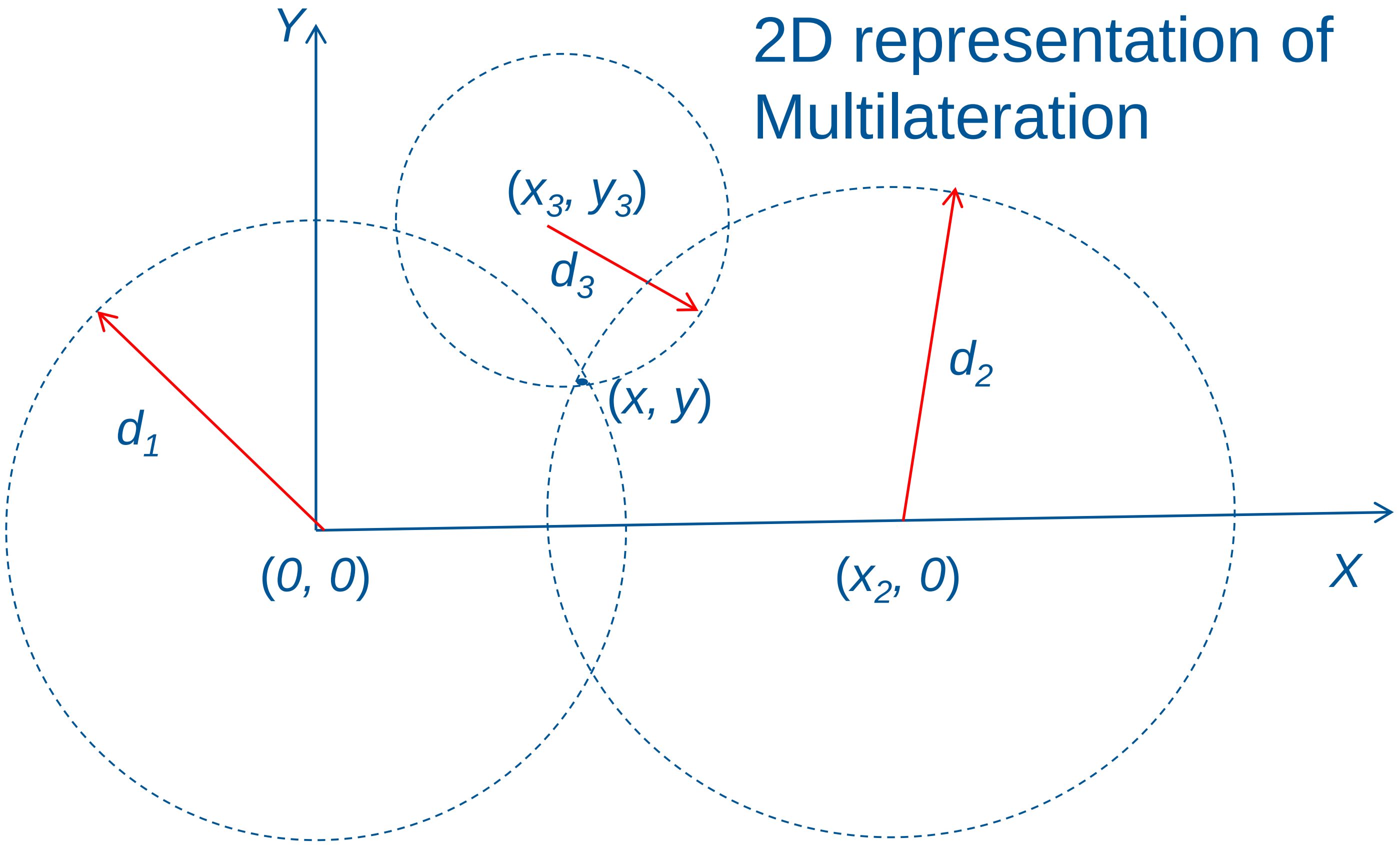
Multilateration…

- … is the process of determining absolute (or relative) locations of points by measurement of **distances** using the geometry of circles or spheres

- *If instrument locations are known e.g.*
  - Origin
  - Distance x_2 along x axis
  - On X-Y plane at (x_3, y_3)
- Then measurements d_1, d_2 and d_3 are sufficient to locate uniquely target coordinates (x, y)
- In 3D and if instrument locations are **<u>not known</u>**, we need more information…

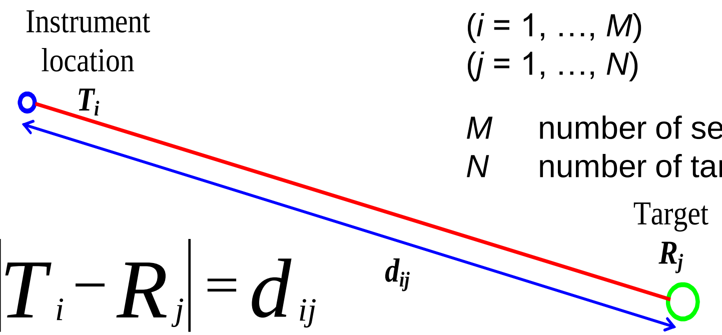
2D representation of Multilateration



Multilateration

Determine coordinates by measuring range, d_{ij} from M instrument locations, T_i, to N targets located at coordinates R_j.

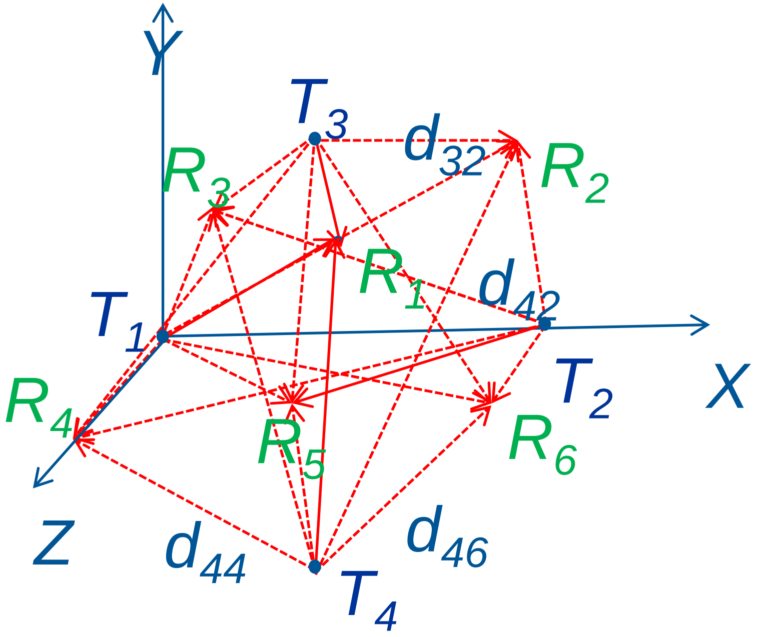
- **Self-calibrating** if $M \geq 4$ and $N \geq 6$
- Increasing N, M gives data redundancy -> **uncertainty estimates**
- **Traceable to SI** (if d_{ij} is traceable)
- Can extend model equation to include other **systematic factors** – and **compensate** for them with full **traceability**
- Can achieve coordinate uncertainty ≈ range uncertainty



$(i = 1, \ldots, M)$
$(j = 1, \ldots, N)$

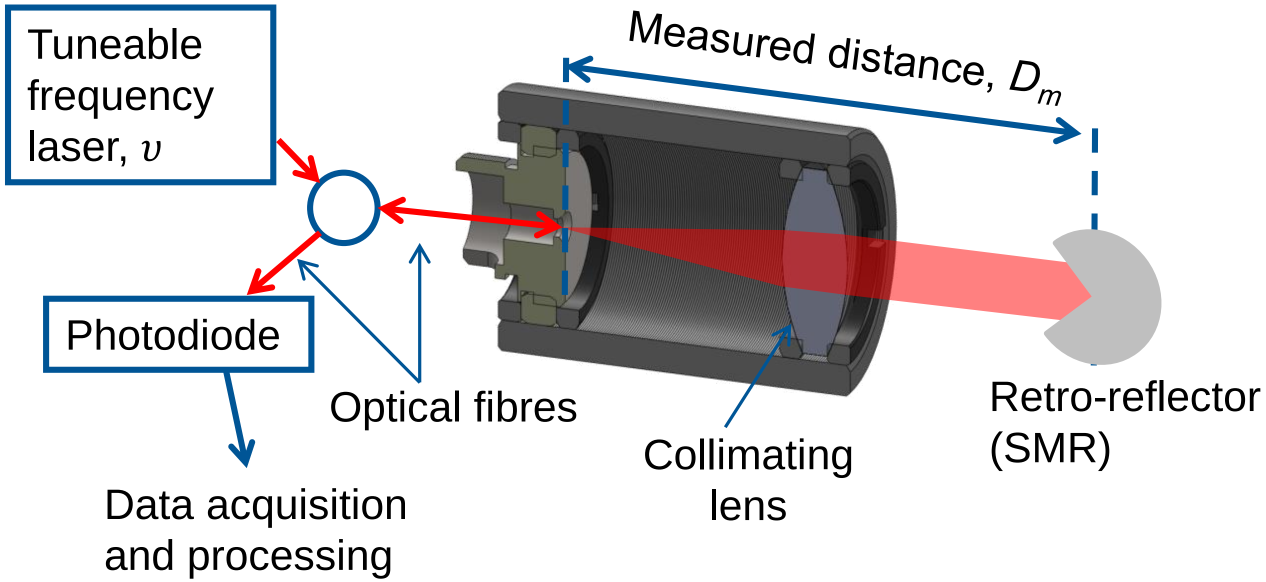
M number of sensors
N number of targets

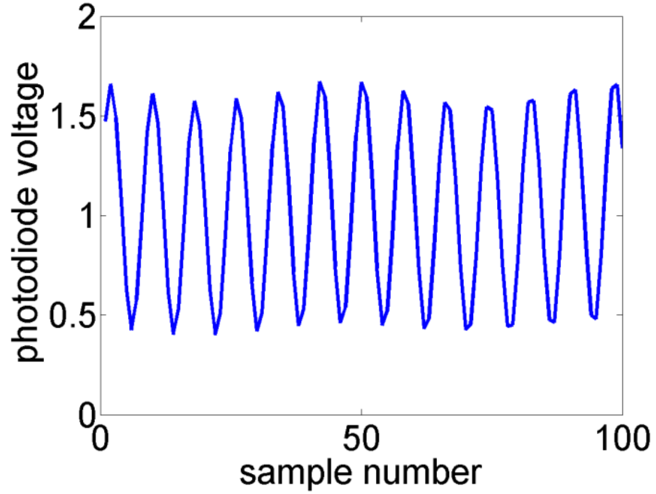
$$|T_i - R_j| = d_{ij}$$



How do we determine absolute distance to multiple targets simultaneously?

Conventional Frequency Scanning Interferometry (FSI)



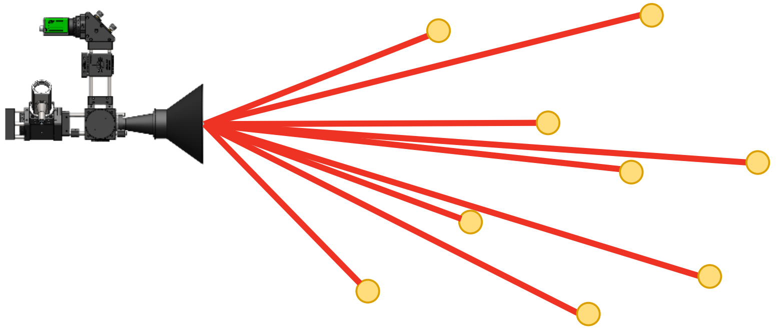


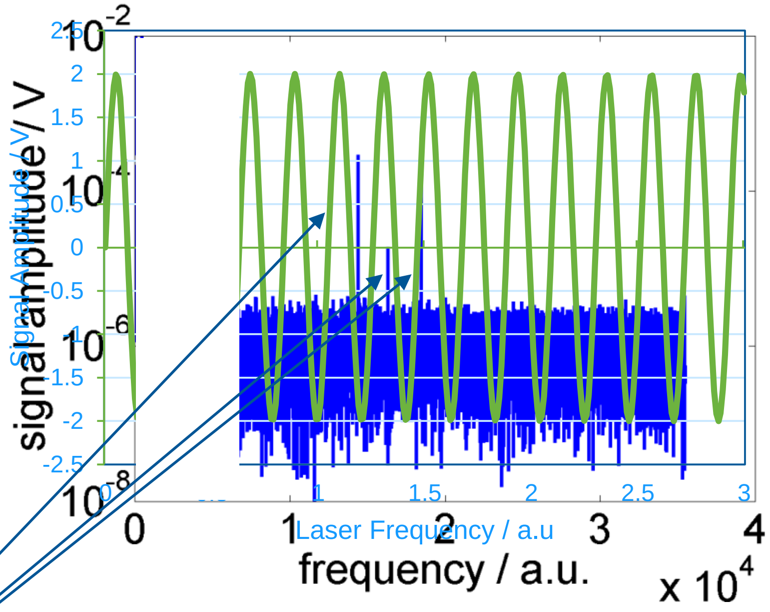
Beat interference signal at detector

$$D = c\frac{N}{2\Delta\nu}$$

D = measured distance
c = speed of light (defined)
N = Number of cycles of signal
$\Delta\nu$ = change in laser frequency

Extracting signals from multiple targets





Fourier transform

Each target shows up as a separate peak in the frequency domain

$$D_j = c \frac{f_j}{2 \, dv/dt}$$

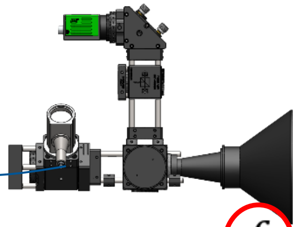
Traceability to SI:
Gas cell frequency reference

Variable Frequency Laser, ν

Gas Cell

Photodiode

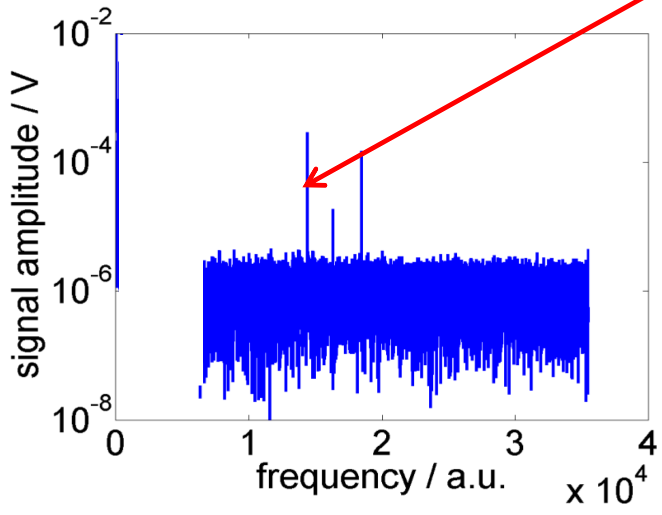
HCN gas cell

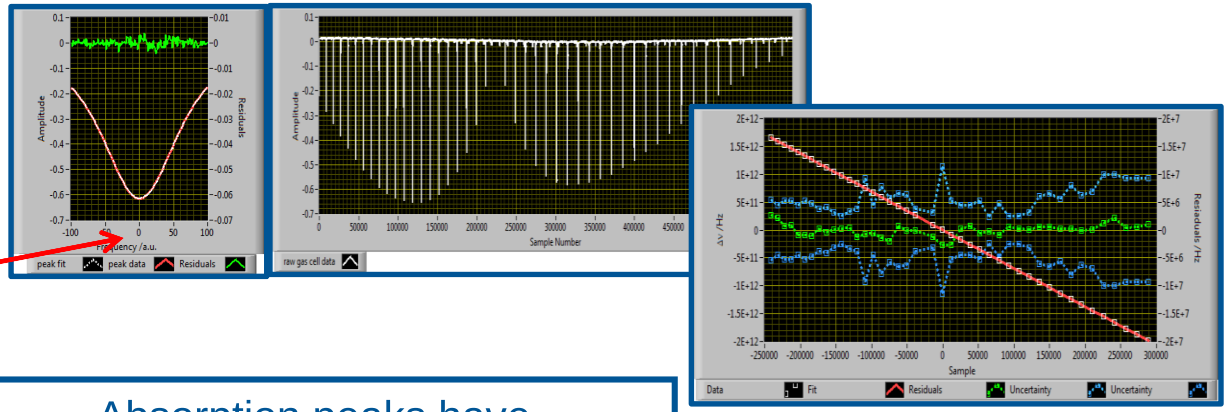


Photodiode

Fourier transform

$$D_j = c\frac{n_j}{2\Delta\nu} = \frac{f_j}{2\frac{d\nu}{dt}}$$





Absorption peaks have known and constant frequencies

Gas cell provides **traceability** to the second and to the metre via the defined speed of light, *c*. **Uncertainty of ~ 1 ppm**

Measuring multiple targets simultaneously

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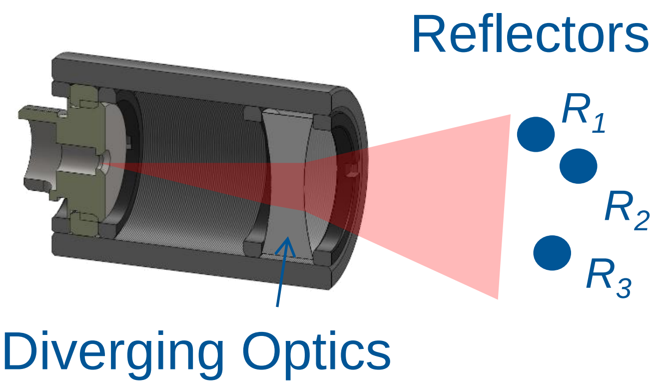
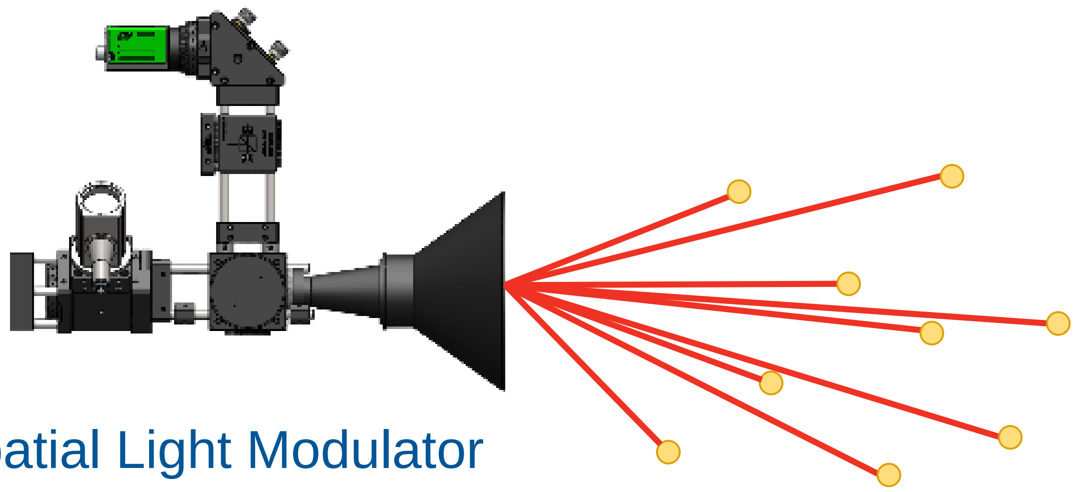
Short range
- Divergent lens system
- Cheap sensor heads



Long range
- Near-collimated beams
- Multiple beams
- Steerable beams with tracking



Spatial Light Modulator + Optics + Camera

NPL's Coordinate Metrology System

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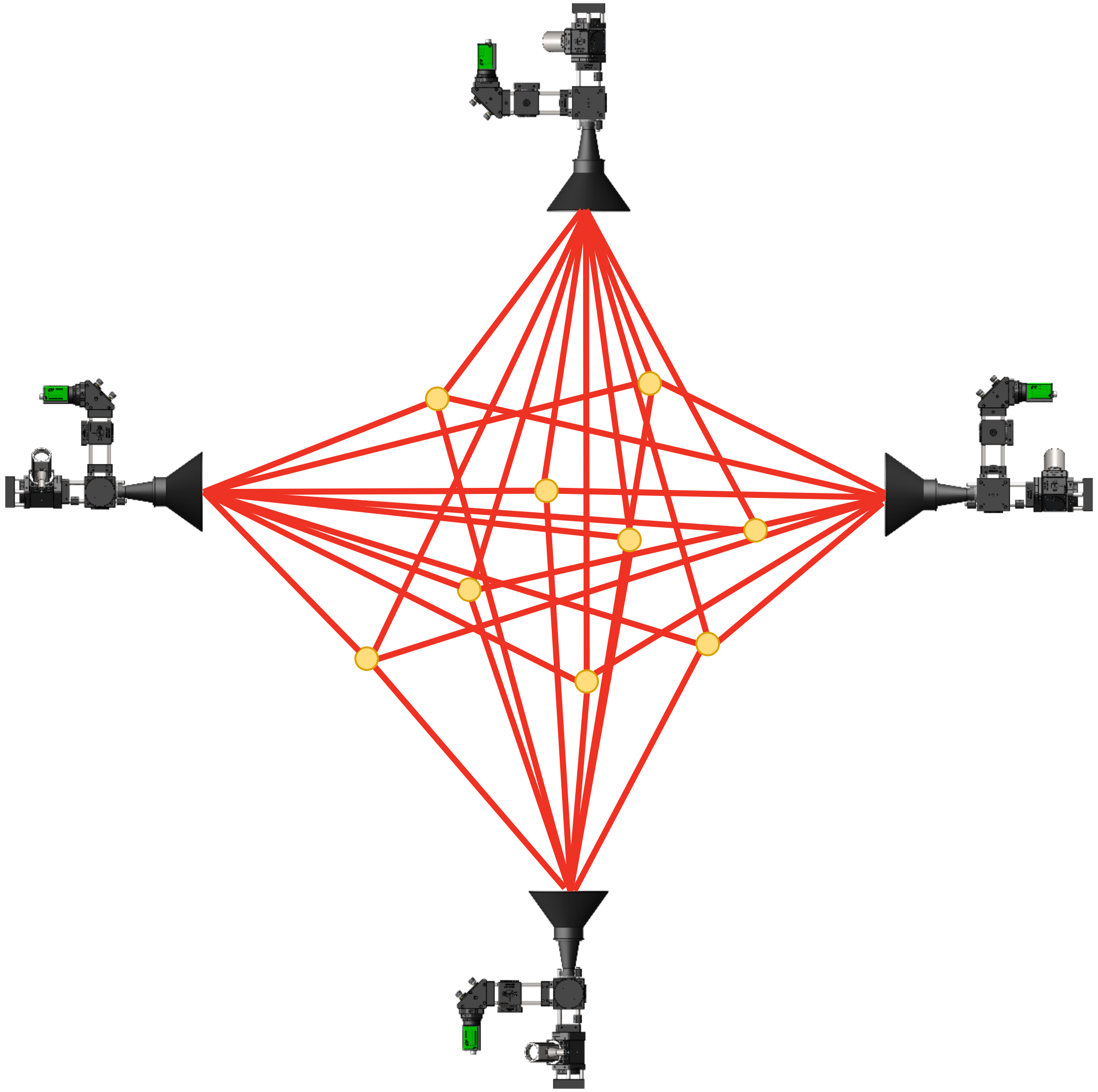
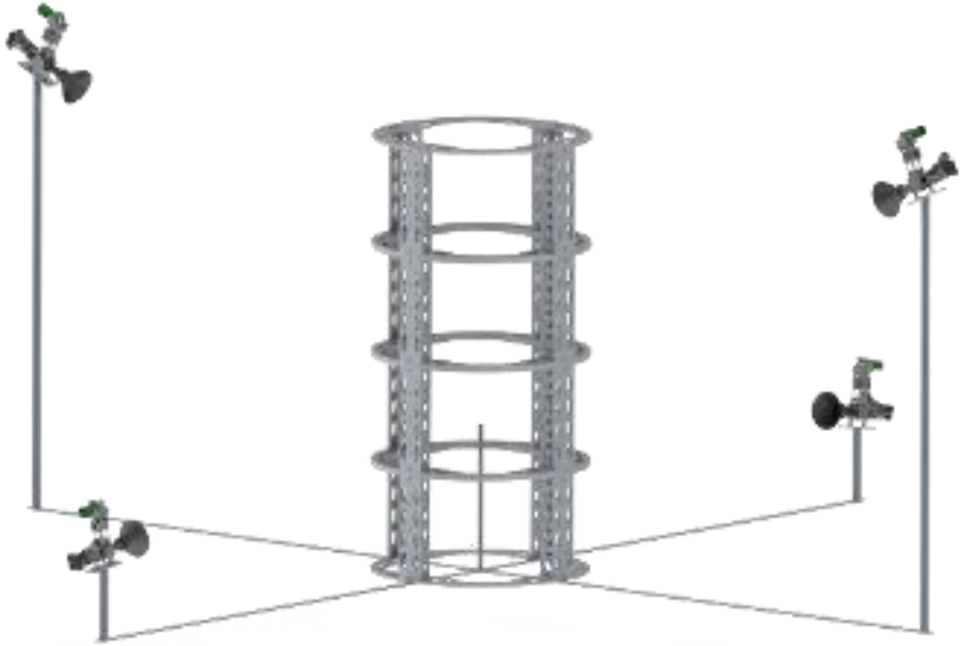
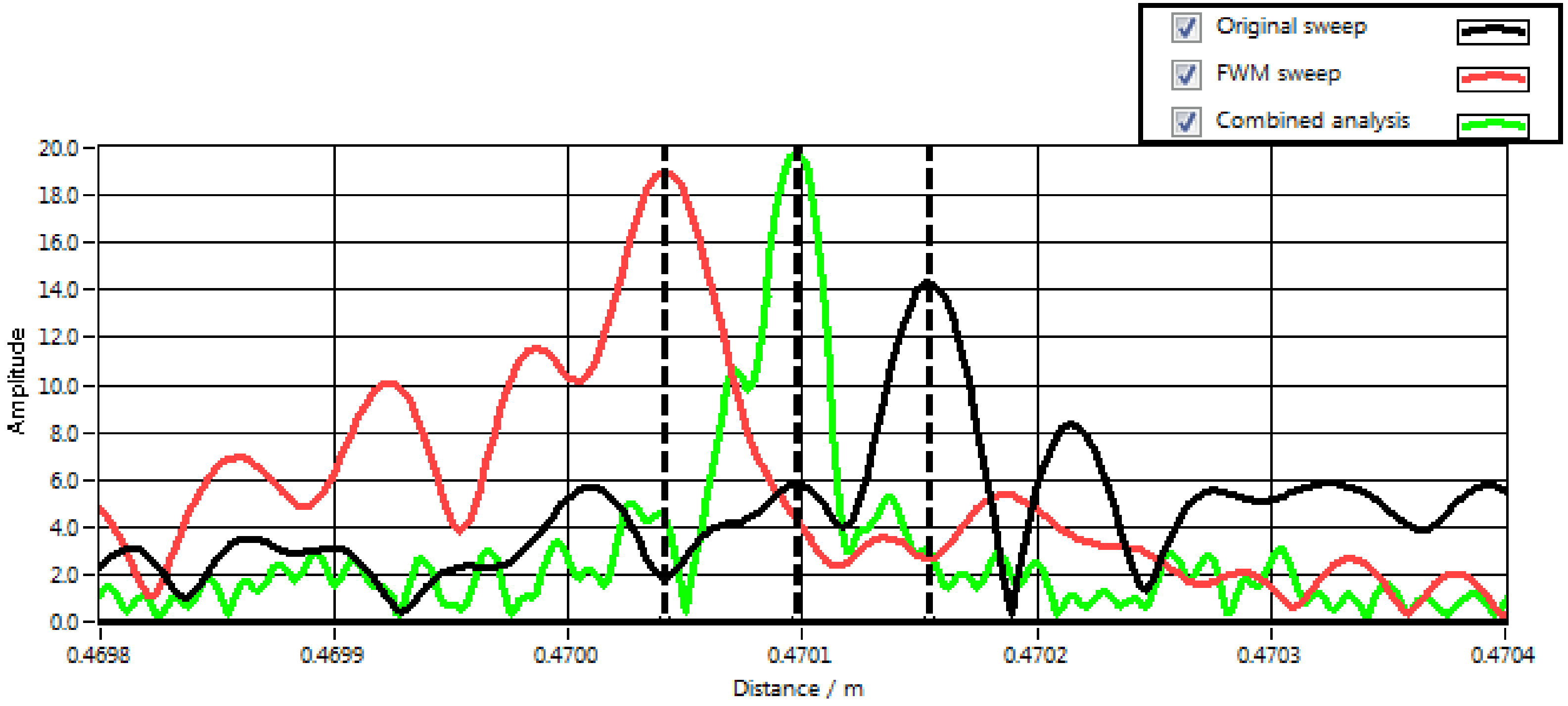


Aim for an operating volume of 10 m x 10 m x 5 m and uncertainty of < 50 µm

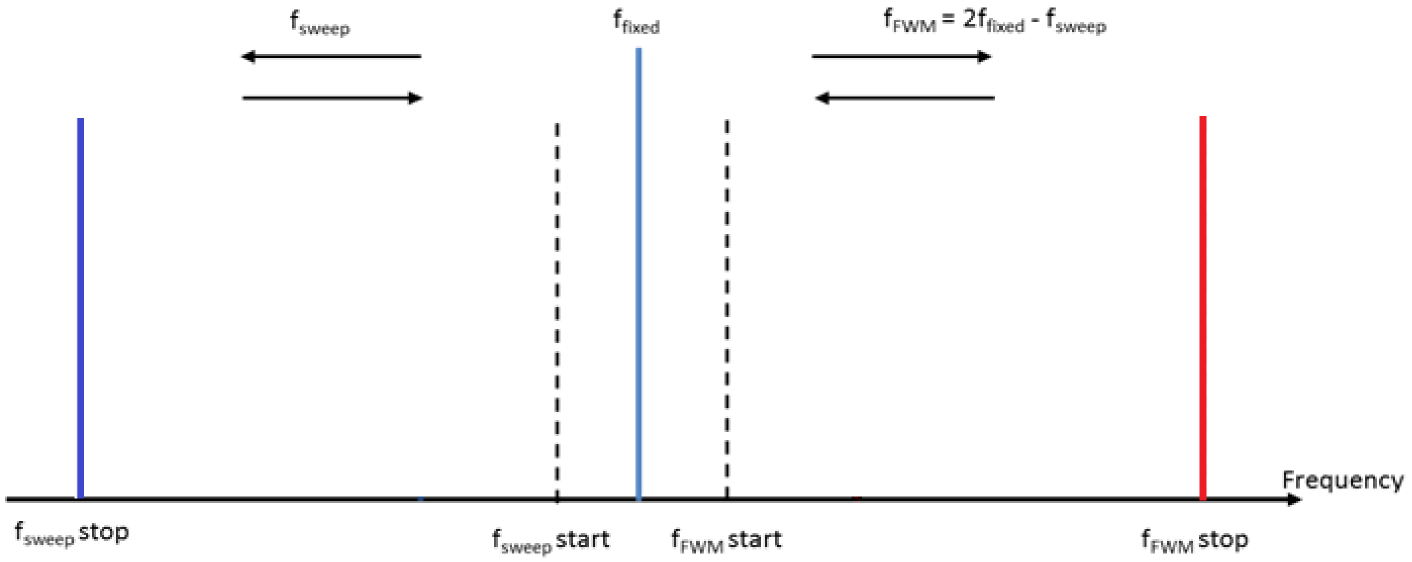


Vibration compensation



- Conventional solution is to use two lasers; one sweeps up, the other down in frequency
  - Expensive
  - Ideally need to synchronise the sweeps

Vibration compensation



- We use (degenerate) Four Wave Mixing (FWM)
  - A non-linear optical effect
  - Takes pump laser (fixed frequency, F_1), signal laser (tunable, F_2) generates new signals,

$$F_{3,4} = 2F_1 \pm F_2$$

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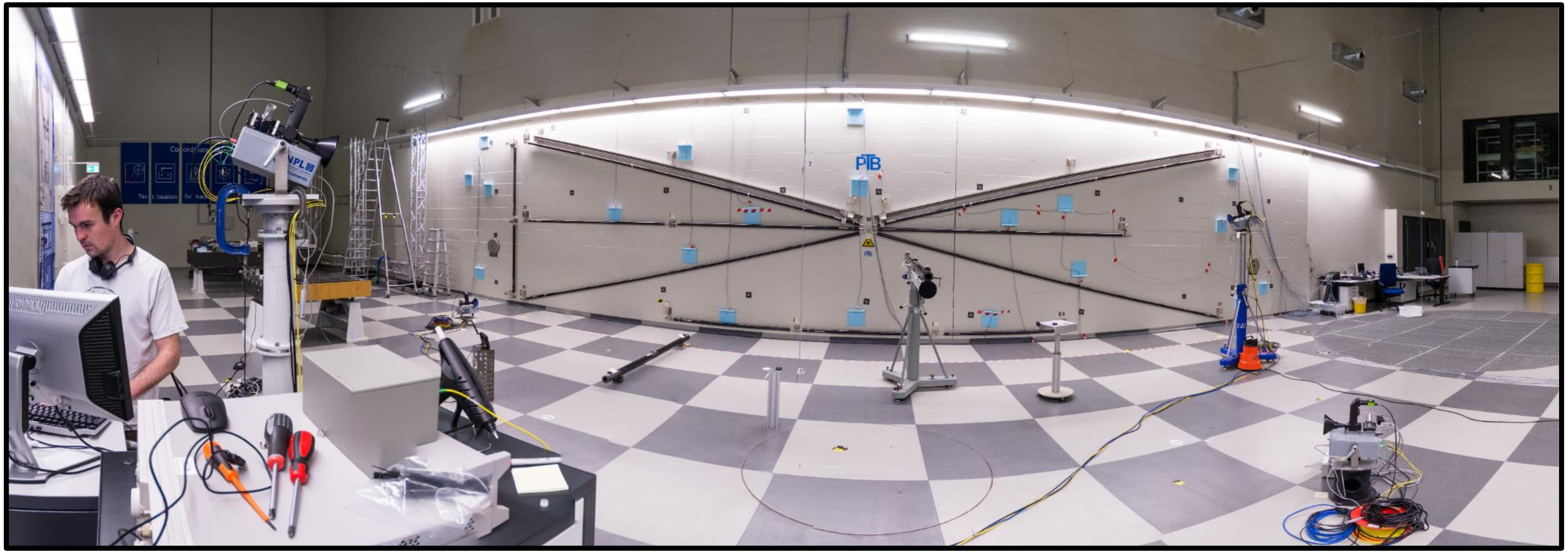
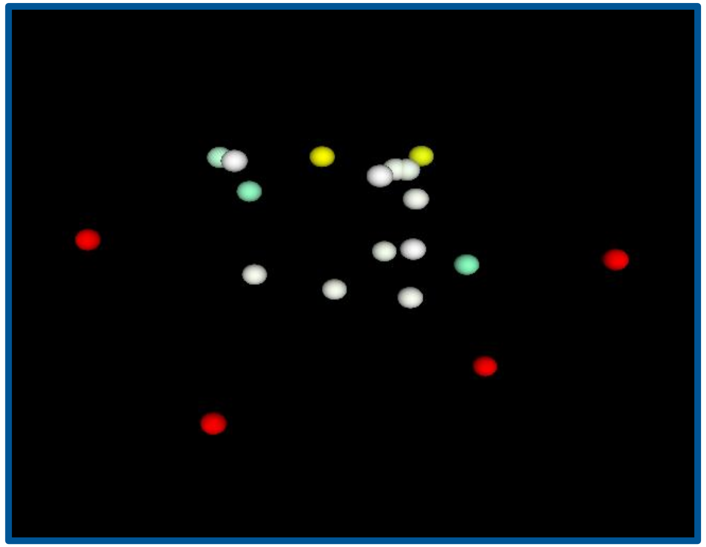
Multilateration Results – Long Range

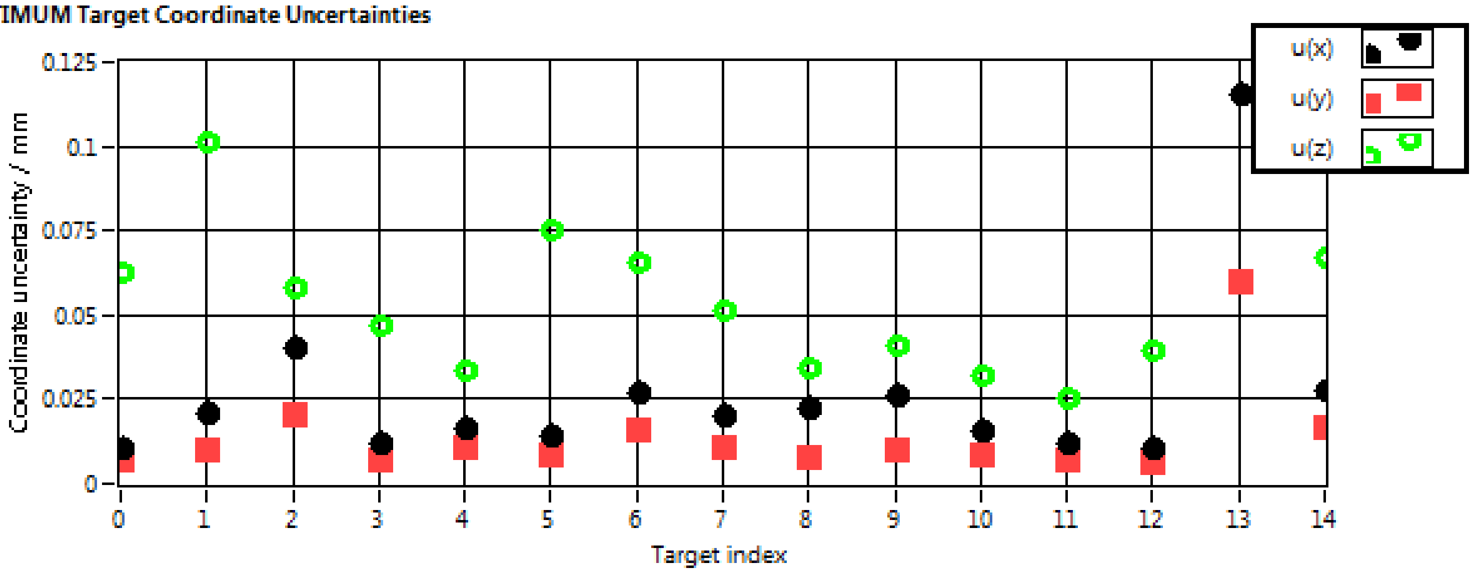


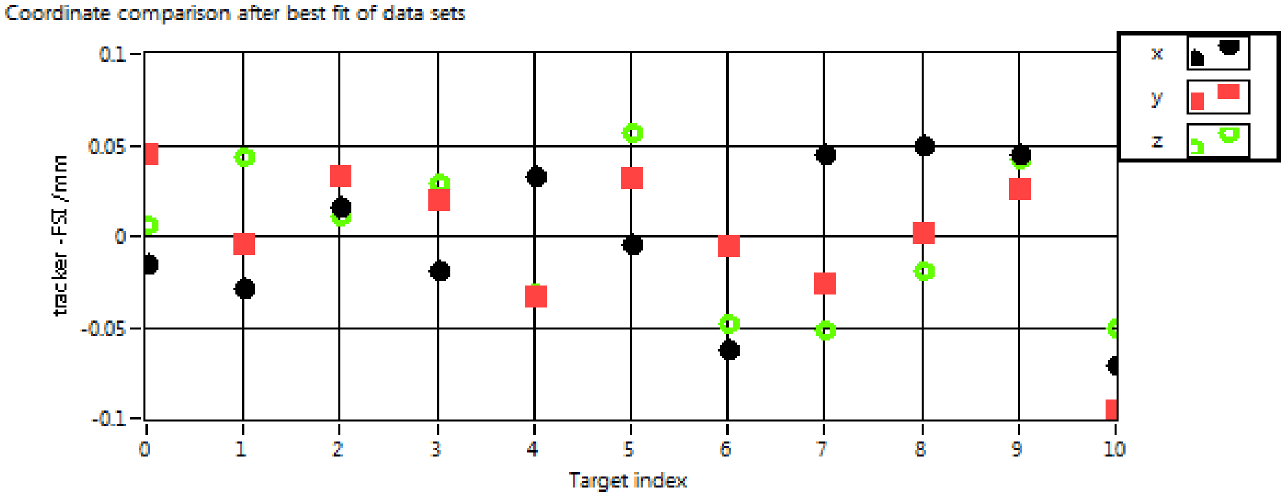
- 8 x 5 x 2.5 m measurement volume
- 4 sensor heads, 15 targets
- Targets measured simultaneously
- Max distance = 8.328 m
- Min distance = 3.240 m
- Angular FoV = 70°

Multilateration Results – Long Range



Multilateration solution, sensors red, targets non-red



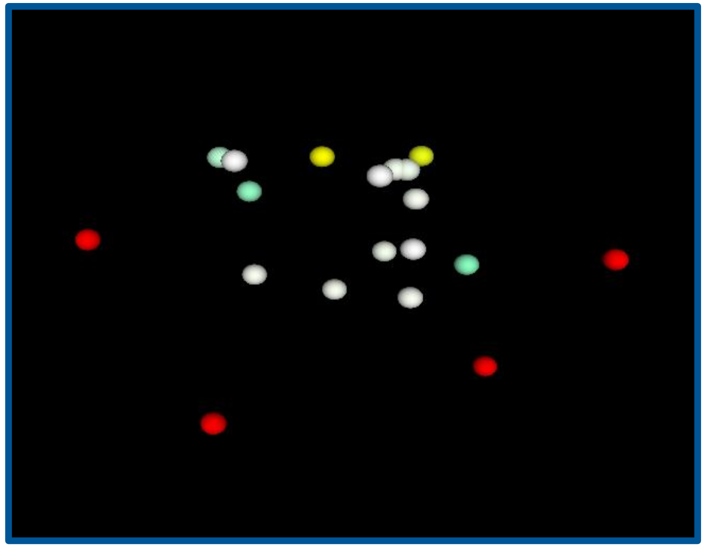


- Averaged up and down sweeps
- RMS coordinate uncertainties;

  x = 22 μm, y = 12 μm, z = 57 μm
- Comparison with laser tracker coordinates:

  RMS difference of 40 μm

Multilateration Results – Long Range



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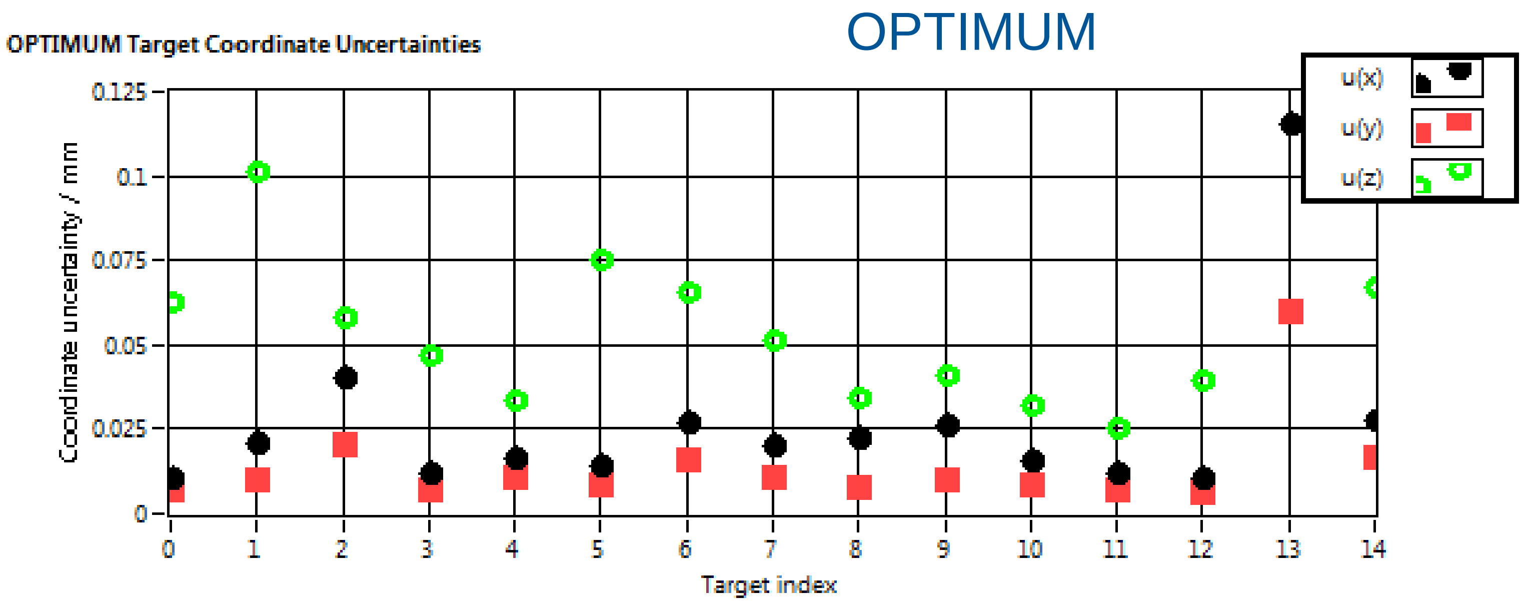
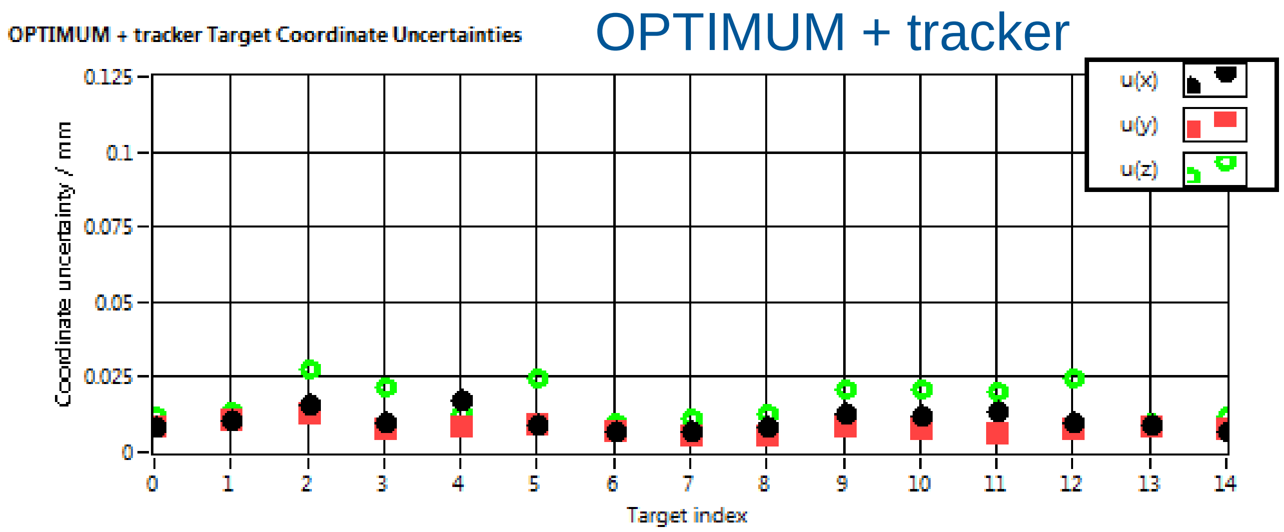
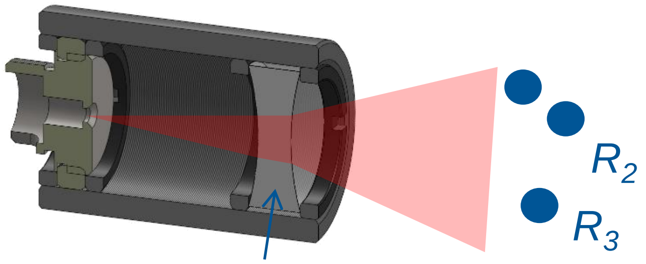


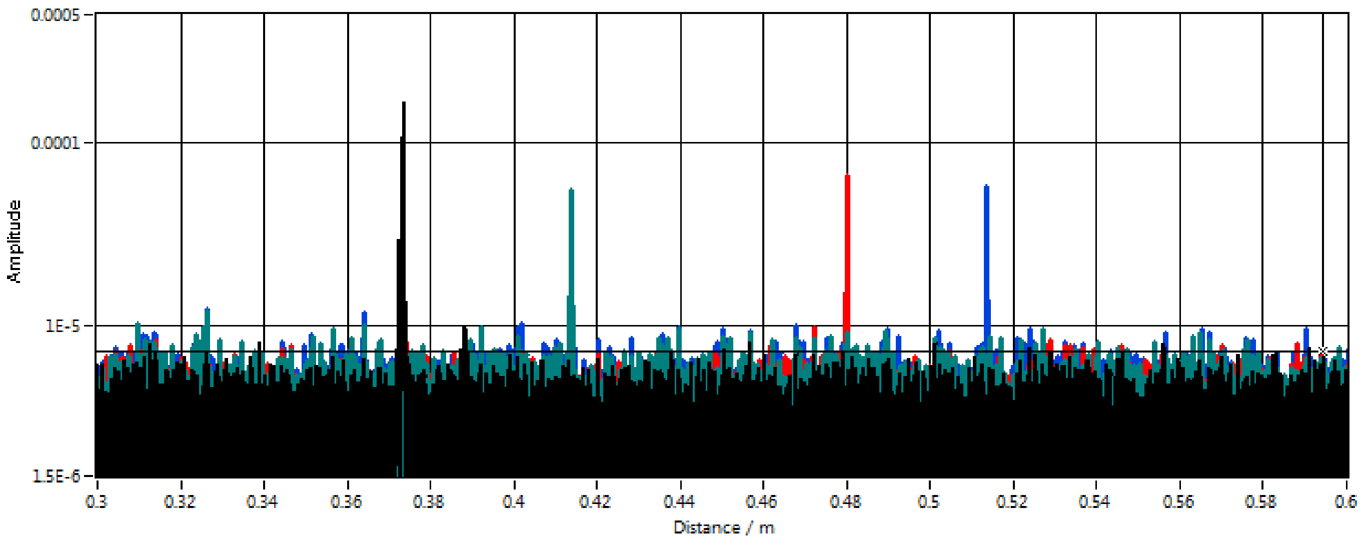


- Introducing the laser tracker into the multilateration network
- RMS coordinate uncertainties;
  x = 12 µm, y = 9 µm, z = 19 µm

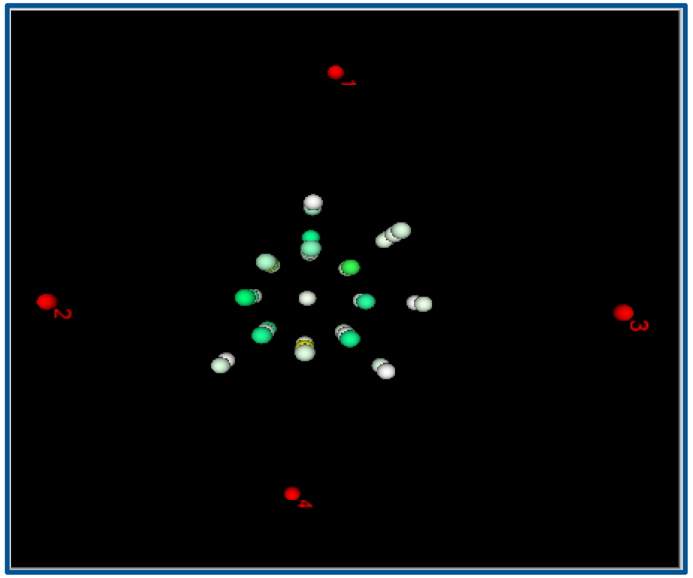
Multilateration Results – Short Range

- 3D stage follows determined path with target
- attached
- FSI measurements taken at each point
- Scan time of 15 ms
- FoV of 70˚





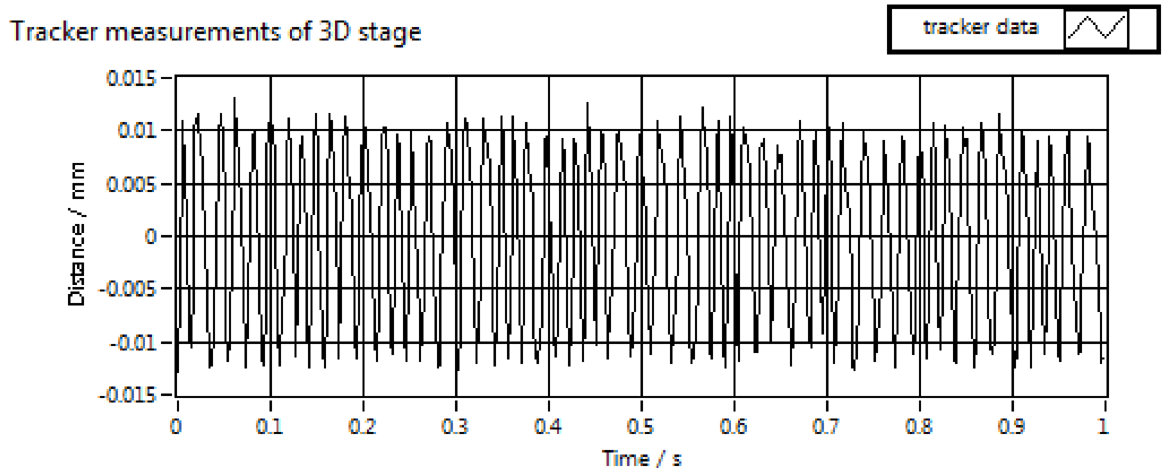
Distance measurement to target from each sensor



Multilateration solution,
sensors red, targets non-red

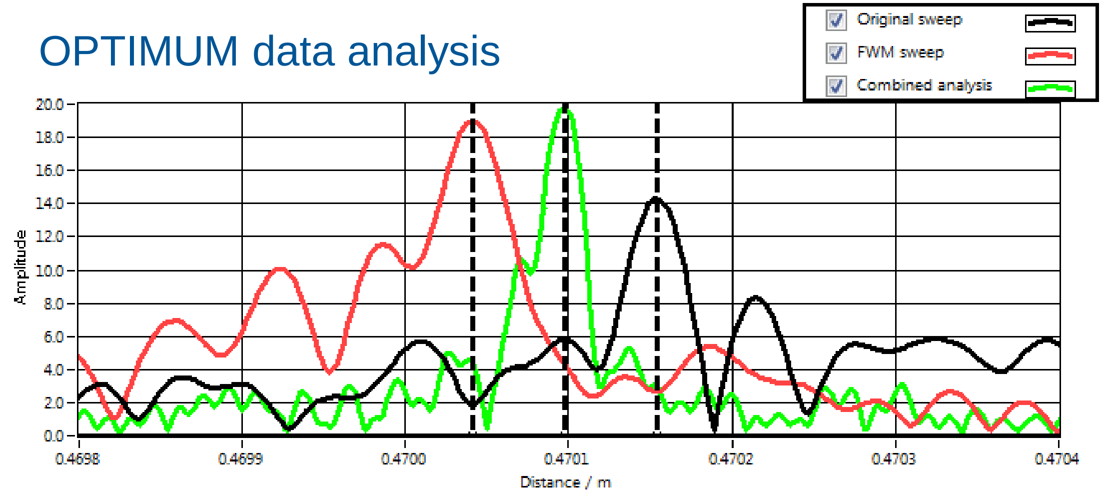
Multilateration Results – Short Range

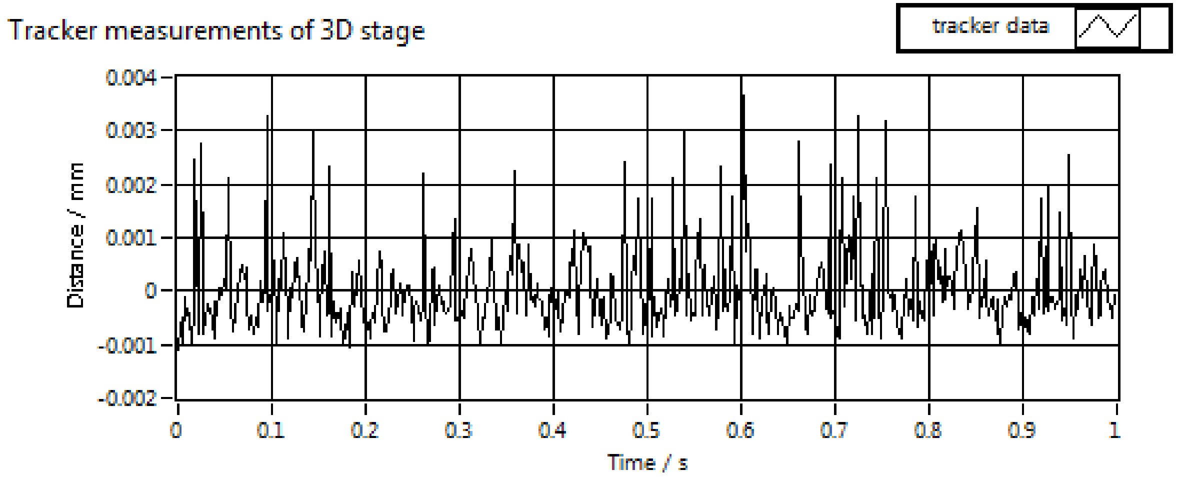
- 3D stage not particularly stable
- Measured with laser tracker - 500 Hz sampling for 1 sec
- Vibration amplitudes of 50 µm when measured with FSI
- Vibration compensation essential!



Laser tracker measuring target attached to 3D stage in a stationary position

OPTIMUM data analysis





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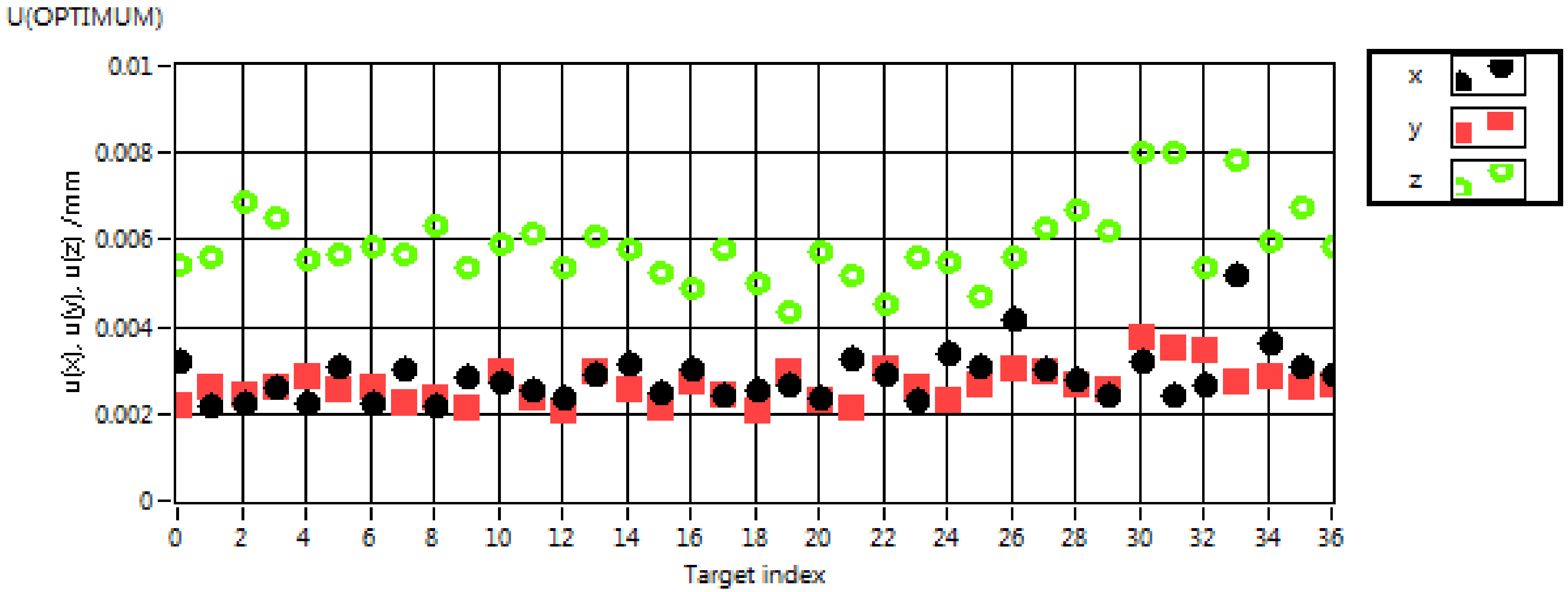
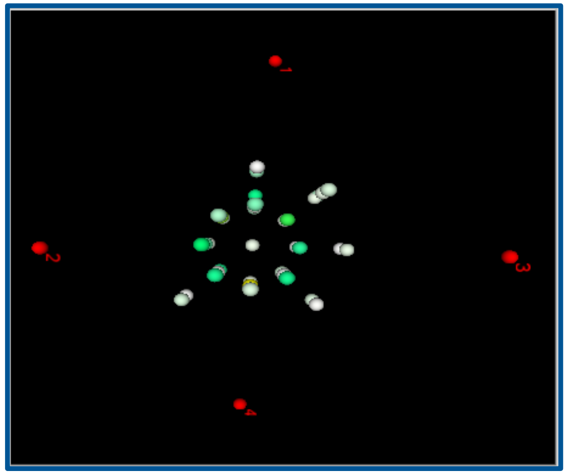
Multilateration Results – Short Range

- RMS Coordinate uncertainties:
  x = 3 µm, y = 3 µm, z = 6 µm
- Again poor geometry in z-axis





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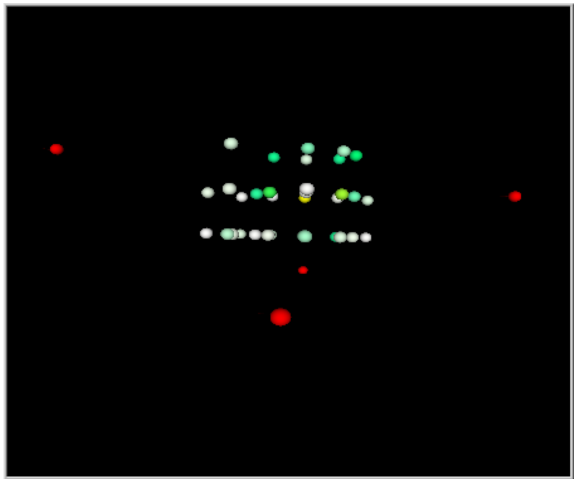
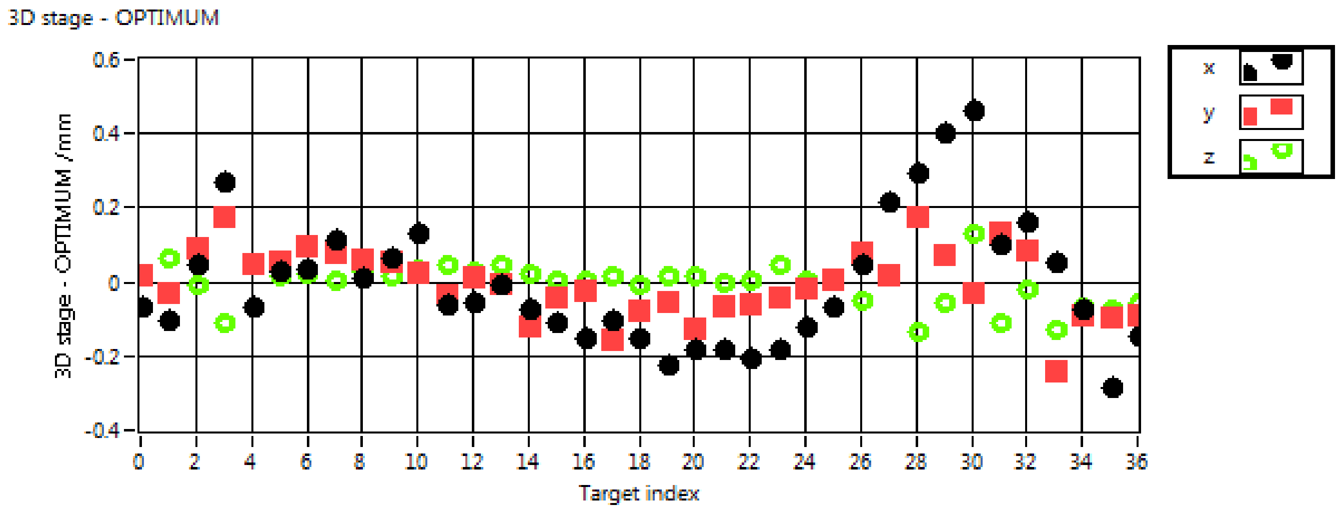


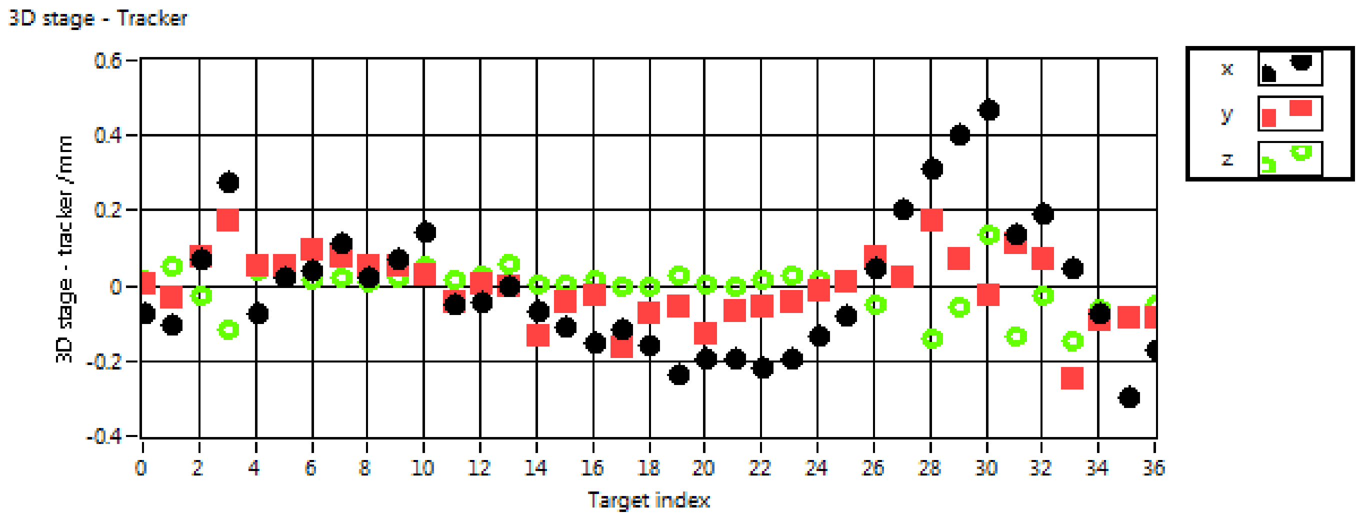
Multilateration Results – Short Range

Comparison with Tracker

- Compared output of OPTIMUM with 3D stage
- But, unfair comparison…
- 3D stage not error compensated

- Compared output of tracker with 3D stage
- Good agreement between the tracker and OPTIMUM





Multilateration Results – Short Range

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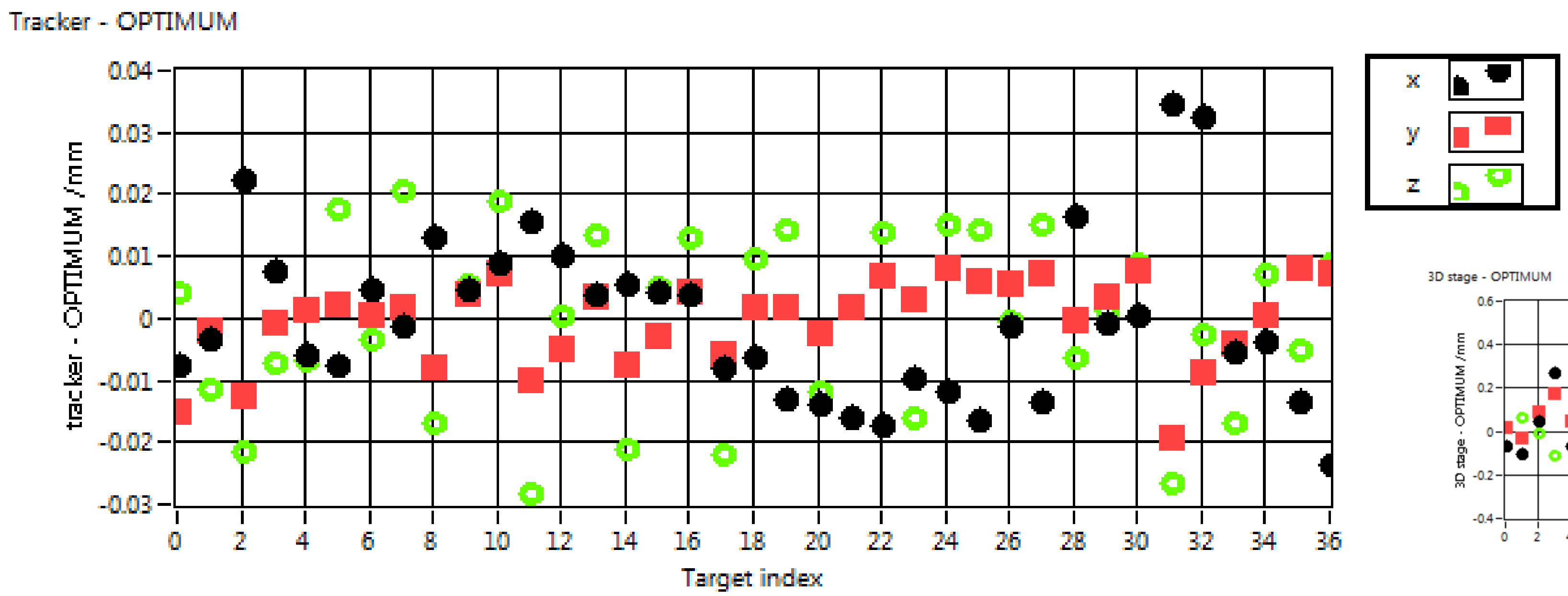

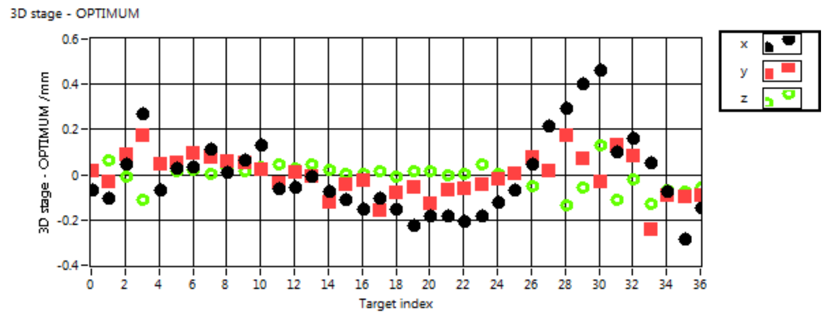

- ± 30 µm difference between OPTIMUM and tracker – but still structure?
- ± 6 µm difference in 3D stage between tracker and OPTIMUM measurements
- Target offset between OPTIMUM and tracker ~5 mm difference – Leads to different roll, pitch, and yaw errors – accounts for observed discrepancy

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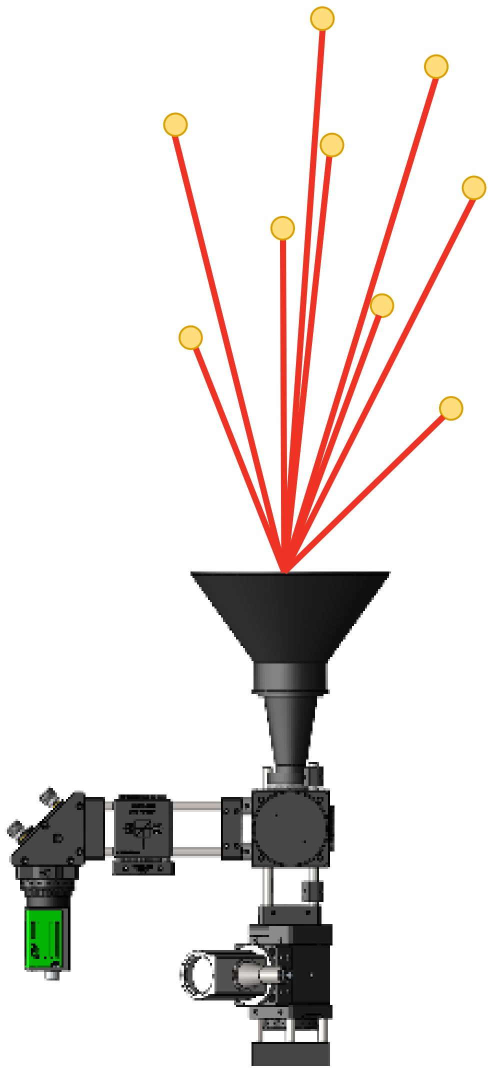
Conclusion

- Two prototype *proof-of-concept* system constructed
  - Short range (simple diverging lens)
  - Long range (SLM + optics + camera)
- Simultaneous FSI to multiple targets over large volume from multiple sensors demonstrated
- Traceability through direct, *in-situ* calibration against a gas absorption cell with an uncertainty of 1 ppm.
- Multilateration determines un-known system parameter, currently sensor locations and offsets as well as target coordinates
- Currently achieving task specific uncertainties of:

  25 µm for long range system

  3 µm for short range system



Thank you

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LUMINAR

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